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# Design Of A Gas Test Loop Facility For The Advanced Test Reactor

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## 1. INTRODUCTION

The Office of Nuclear Energy within the U.S. Department of Energy (DOE-NE) has identified the need for irradiation testing of nuclear fuels and materials, primarily in support of the Generation IV (Gen-IV) and Advanced Fuel Cycle Initiative (AFCI) programs. These fuel development programs require a unique environment to test and qualify potential reactor fuel forms. This environment should combine a high fast neutron flux with a hard neutron spectrum and high irradiation temperature. An effort is presently underway at the Idaho National Laboratory (INL) to modify a large flux trap in the Advanced Test Reactor (ATR) to accommodate such a test facility [1,2].

The Gas Test Loop (GTL) Project Conceptual Design was initiated to determine basic feasibility of designing, constructing, and installing in a host irradiation facility, an experimental vehicle that can replicate with reasonable fidelity the fast-flux test environment needed for fuels and materials irradiation testing for advanced reactor concepts. Such a capability will be needed if programs such as the AFCI, Gen-IV, the Next Generation Nuclear Plant (NGNP), and space nuclear propulsion are to meet development objectives and schedules. These programs are beginning some irradiations now, but many call for fast flux testing within this decade.

### 1.1. The Advanced Test Reactor

The ATR was originally commissioned in 1967 with the primary mission of materials and fuels testing for the United States Naval Reactors Program. The ATR is fueled with highly enriched uranium, with light water coolant and a beryllium reflector, and is the highest power research reactor operating in the United States. Its large test volumes make it attractive for irradiations of materials and components. The ATR is designed to evaluate the effects of intense radiation on material samples, especially nuclear fuels, and provides large-volume, high-flux test locations. A unique serpentine fuel arrangement provides 9 high-intensity thermal neutron flux traps and 68 additional irradiation positions inside the reactor core reflector tank, each of which can contain multiple experiments. The four flux traps positioned within the corner lobes of the reactor core are almost entirely surrounded by fuel, as is the center position. Four other flux trap positions between the lobes of the core have fuel on three sides. The curved fuel arrangement brings the fuel closer on all sides of the flux trap positions than is possible in a rectangular grid. Effects from years of radiation in a normal power reactor can be duplicated in months or even weeks in the ATR. The ATR has a maximum thermal power rating of 250 MW with a maximum unperturbed thermal neutron flux rating of $1.0 \times 10^{15}$ n/cm$^2$–s; however, in recent years it has only occasionally operated at thermal powers greater than 110 MW.

### 1.2. GTL Performance Requirements

Early in the conceptual design activity, the potential customer list for the GTL included not only programs needing fast flux testing capability, but also thermal fission programs where test objectives included dynamic effects associated with particular coolant flow regimes. As the various concepts were conceived and analyzed, it became apparent that it was not practical to meet all the requirements of all the programs in a single facility. In particular, because of fundamental issues connected with reactor safety, it appeared unwise to consider placing exotic coolant loops, such as liquid metal, molten salt, and supercritical water, in the ATR. Hence, emphasis has since been placed clearly on fast-flux testing for fuels and materials development and qualification.

Table 1 lists selected performance requirements for the GTL design effort. The performance characteristics listed in the "Required" column are those considered the minimum acceptable for a fuel testing environment. Those listed in the "Desired" column reflect values that would extend the capability and make the GTL more serviceable to a wider group of customers or improve the extent to which GTL could meet customer needs.

**Table 1.** Selected performance requirements for the Gas Test Loop.

| Parameter | Required | Desired |
|---|---|---|
| Test volume length (cm) | 15.5 | 89 |
| Test volume diameter (cm) | 2.54 | 5.9 |
| Fast flux intensity (n/$cm^2$.s, E>0.1 MeV, unperturbed) | 1.0E+15 | 3.0E+15 |
| Fast/thermal neutron flux ratio | >15 | >100 |
| Flux uniformity in test space (%) | ±10 | ±5 |
| Heat Removal Temperature (°C) | 500 ±15 to 1,100 ±20 | 500 ±15 to 1,830 ±50 |
| Maximum Test Article Linear Heat Rate (W/cm) | 2,300 | 3,000 |
| Total Heat Flux (kW) | 200 | 3,600 |
| Design Lifetime (years) | 30 | Life of Program |

## 2. SCOPING STUDIES

Given that the GTL will be located in the ATR, a thermal spectrum reactor, conceptual design studies have shown that booster fuel will be required to supplement the fast neutron flux coming from the reactor and a thermal neutron absorbing structure will be necessary to harden the neutron spectrum. Without the booster fuel, the reactor lobe power required to get the desired fast flux level would be well beyond feasible levels. With the booster fuel, the reactor can operate within its acceptable power range.

### 2.1. Parametric Studies

Analyses were conducted to evaluate potential fuel materials and enrichments, geometries, and coolants. At the initial stage of the study, all potential options were considered viable until eliminated by either practical (design or safety) considerations or failure to meet the requirements for the test loop. Parametric studies were conducted to evaluate candidate designs. Detailed studies were conducted on promising candidates emerging from the parametric studies. These more detailed studies included thermal-hydraulic calculations and evaluation of material property limitations.

The neutronics models used for the parametric studies were based on a large in-pile tube (IPT), specifically the NW lobe, of the ATR using a generic MCNP model. Version 4C [3] of the MCNP code was used in the analysis. A surface source was modeled at the inner radial boundary of the current IPT baffle to decouple the GTL from the remainder of the reactor core. This approximation greatly increased the calculation speed and allowed more candidate designs to be considered for the selection process. A full-core ATR MCNP model (Figure 1) was used to analyze the design model selected from the initial scoping studies, so that the full detail of the GTL design could be included.

One option considered was simply increasing the lobe power to increase the total neutron flux. Four other models were also used: (1) an annular plate fuel model, (2) a pin fuel model, (3) an ATR fuel plate model, and (4) a depleted uranium slab model. Parametric studies, varying fuel and coolant channel dimensions, fuel materials, enrichments, and densities, thermal neutron filter materials, and irradiation test volume dimensions, were performed for each model.

The parameters used to evaluate each candidate design option were:

- Fast neutron flux intensity at 40 MW lobe power

- Ratio of fast to thermal neutron flux
- Test space diameter
- Booster fuel clad surface temperature
- Booster fuel centerline temperature
- Booster fuel replacement frequency

Each performance criterion had an associated utility function, designed to mathematically express the worth to the program of a particular value of each parameter. Weighting factors were applied to each utility function value to make the final selection from among the best candidate designs. In each case, the required value was assigned a utility of 0.5. Desired values were assigned a utility of 0.9, and the maximum believed achievable was assumed to have a unity utility. Analytic functions were then developed that passed through each of these points.

The best candidates designs from the parametric studies were:

- Annular Ring configuration in which the booster fuel consists of three circumferential rings of uranium silicide fuel;
- ATR Plate configuration in which slightly modified ATR fuel plates are arranged in a circumferential array that is not a ring or set of rings;
- Low Enriched U configuration where a relatively heavy section ring of slightly enriched uranium metal surrounded by a thin highly enriched layer constitutes the booster fuel.

Table 2 shows the comparison of the options considered during the final selection process. The first line for each concept is the utility function score for the parameter whose value is listed in the second line. Scores in the last column are weighted sums of the utility functions using the parameter weights at the bottom, established by consensus engineering judgment.

**Table 2.** Results of criteria application to alternative concepts.

| Design Concept | Fast Flux (n/cm$^2$/s) | Fast/Thermal | Test Diameter (cm) | Clad Surface Temp. (F) | Fuel Centerline Temp. (F) | Fuel Replacement Frequency (1/y) | Score |
|---|---|---|---|---|---|---|---|
| Annular plate | 0.48 | 0.73 | 0.95 | 0.67 | 0.96 | 0.81 | 0.69 |
| Parameter value | 9.79E+14 | 30 | 8 | 339 | 471 | 3 | |
| ATR plate | 0.45 | 0.69 | 0.88 | 0.00 | 0.78 | 0.81 | 0.55 |
| Parameter value | 9.50E+14 | 26 | 5 | 419 | 563 | 3 | |
| Low-enriched U | 0.17 | 0.61 | 0.95 | 0.83 | 0.00 | 0.94 | 0.50 |
| Parameter value | 7.62E+14 | 20 | 8 | 315 | 1403 | 1 | |
| **Weights** | 0.35 | 0.20 | 0.15 | 0.15 | 0.10 | 0.05 | |

From this evaluation, the most desirable concept for the booster fuel assembly is clearly the annular plate configuration.

### 2.2. Detailed Analysis Methods and Models

Detailed neutronics calculations were performed with the MCNP code, version 4C. This code was used for calculation of neutron fluxes and energy deposition rates. For the neutronics modeling, two models were developed – one for calculations at the beginning of the driver fuel cycle, and a second for depletion calculations. The beginning-of-cycle (BOC) static model, shown in Figure 1, has an explicit representation of plates 1-4 and 16-19, with plates 5-15 smeared into a single region. The depletion model uses three radial fuel regions (plates 1-4, 5-15, and 16-19, respectively) and seven axial regions per fuel element. Both models have a complete description of the experiments used during cycle 134AB, which was the first cycle after the core internals changeout of 2004-5.

The fuel models were based on ATR loading patterns generated with the PDQ code [6]. Fresh fuel element nuclide concentrations were calculated from the known uranium and boron loadings of fresh ATR fuel elements. The recycled fuel element concentrations were scaled from the fresh fuel nuclide concentrations based on the fractional element burnup. Fission product concentrations were scaled from Oak Ridge Isotope Generation and Depletion (ORIGEN2) code [7] calculations for fresh ATR fuel elements, with the scaling based on the element fractional burnup and the PDQ $^{149}$Sm concentration.

Each radial fuel zone of the driver core in the depletion model is subdivided into seven axial zones. The top and bottom three axial zones are equal sizes while the center axial zone is twice the length of the others. The large center section is justified due to the flat axial flux profile near the centerline of the core. The result is 840 individual depletion zones in the driver fuel. The only change to the booster fuel model from the static model is the division into seven axial zones to match the axial zones of the driver fuel. The total number of depletion zones in the booster fuel is 84.

The MOCUP code [4] is used to couple the MCNP depletion model with ORIGEN2 to simulate the fuel material through several ATR cycles. The output from the first MCNP run is used in ORIGEN2 to calculate the generation and depletion of the actinides, fission products, and boron. The new material compositions are calculated from the ORIGEN2 output and updated in the next MCNP input file by MOCUP.

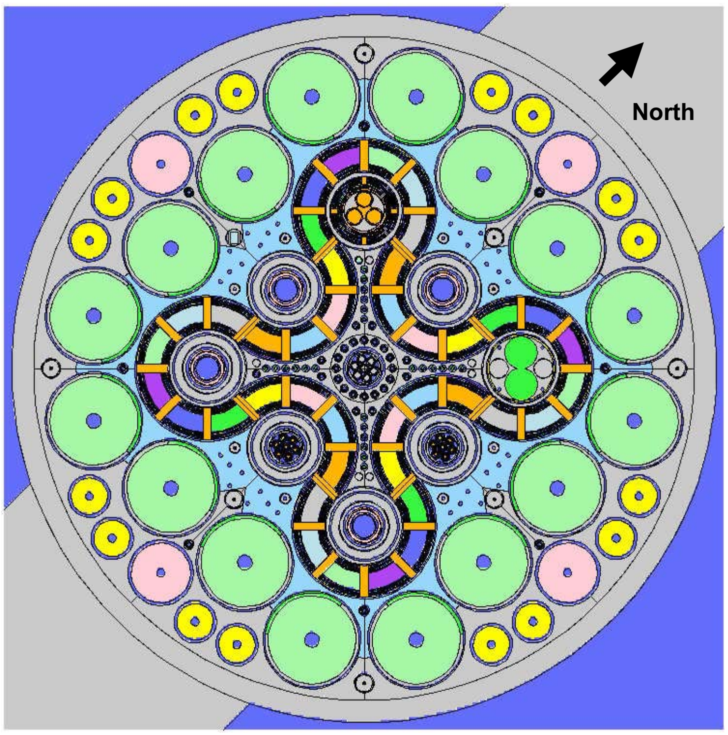


Figure 1.  Axial cross section of the MCNP ATR model used for the GTL design analyses.

Each ATR cycle is divided up into multiple MOCUP (depletion) time steps to model more accurately the fuel burn-up. After each MOCUP step the shim cylinders are adjusted in new MOCUP modified MCNP input file to provide the correct power split and a $k_{eff}$ of ~1.00. The next depletion cycle is then run using the new MCNP input file. These depletion steps are run enough times to simulate a complete ATR cycle at which time the booster fuel is decayed for an outage of seven days using ORIGEN2. A new representative driver core loading is then put into the ATR model and another ATR cycle is simulated. This process continues until the combination of the booster fuel and driver fuel no longer provide the desired flux level in the GTL test space.

Thermal-hydraulic (TH) calculations were performed with the RELAP5 code, version 2.36 [5]. Heat (energy deposition) rates from the MCNP calculations were used as input for the TH analyses. A RELAP5 model was constructed to simulate the thermal-hydraulic response of the conceptual design for the GTL configuration. This model includes explicit representations of all the components shown in Figure 3, except that the spacer assemblies were represented only as an occupant of the space with no thermal mass. The model used for the booster fuel is shown in Figure 2. This shows the representation of the booster fuel along with the component numbering scheme. Each of the 12 fuel plates and 16 coolant channels was individually represented, as was the flux trap baffle with ATR driver core cooling flow on the outer circumference.

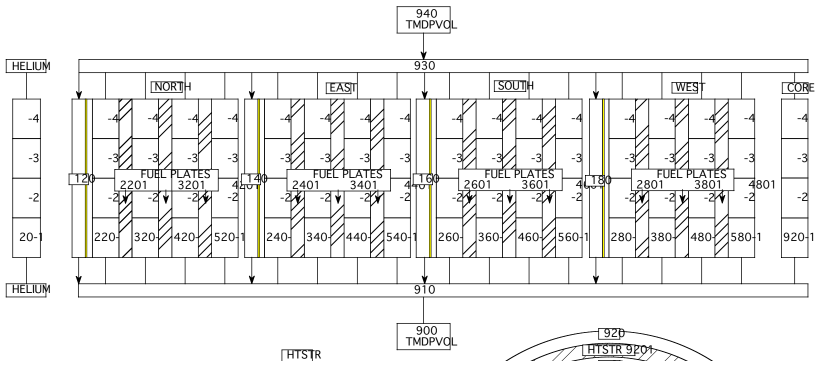


Figure 2. RELAP5 representation of the initial conceptual design of the GTL and booster fuel.

## 3. CONCEPTUAL DESIGN

The conceptual design for the GTL, shown in Figure 3, incorporates a booster fuel assembly, composed of three annular rings of Al6061 clad uranium silicide ($U_3Si_2$) fuel plates, divided into four azimuthal segments, inside one of the ATR's large flux traps. Each annular ring has a different fuel density: 4.8 g/cm$^3$ in the innermost plate, 3.2 g/cm$^3$ in the middle plate, and 2.0 g/cm$^3$ in the outermost plate. A central helium-cooled region can accommodate single tests as large as 7.5cm (3 in.) diameter, or up to three separate tests of 2.5cm (1 in.) diameter. Two separate gas systems are used – one high-velocity helium loop as an active heat removal system for the test facility, and a mixed He/Ne system "sweep gas" system providing temperature control for the tests via gas-gap conductance. The hafnium neutron filter outside the envelope tube has been replaced by hafnium sleeves 1 mm (0.040 in) thick positioned just outside each of the three experiment tubes inside the test space. The outer 0.005 in on each face of the hafnium may be replaced with coatings of Inconel 600 if it is determined that the hafnium will adversely interact with hydrogen impurity in the sweep gas. Spacers inside the test volume are hollow and made of Inconel 600. The pressure tube and envelope tube are now each 3.18 mm (0.125 in) thick and are made of Inconel 600.

During a typical year the ATR performs 5 long cycles (on the order of 48 days) and 3 short cycles (PALM cycles on the order of 14 days). We anticipate that once the GTL is inserted, the other customers will still want 3 short cycles. We anticipate that during a typical year the ATR with the GTL installed will perform 7 long cycles (on the order of 30 days) and 3 short cycles. This change of ATR operating schedule will result in an increase in the need for new ATR driver fuel elements, expected to be in the range of 10 to 20 %.

### 3.1. Gas Coolant Systems

It is estimated that the Gas Coolant Loop will be required to remove approximately 500 kW from the experiment area. In order to meet these cooling needs of the experiment, scoping calculations indicate the loop will have to be operated at a mass flow rate near 2270 kg/hr (5000 lb/hr) at 1.72 MPa (250 psia) with the bulk exit gas temperature of less than 422 K (300°F). It has also been estimated that at operating pressure the entire gas coolant loop will contain around 2.5 kg of helium, which can be supplied by less than three standard size 15.2-MPa (2200-psi) helium bottles.

Each test capsule can be supplied with an independent flowing sweep gas blend (helium/neon is typical of past experiments) to control the test temperature. If a test sponsor has a special test environment need, alternate gases could be introduced into the test capsule through this system. The experiment can be designed such that heat generated in the experiment is transferred by conduction through the gas blend gap to the test capsule wall. The heat is then conducted through the test capsule wall to the heat sink provided by the Gas Coolant Loop. Adjusting the blend of the two control gases, which have different thermal conductivity properties, aids in controlling the temperature of the test specimens. Temperature control will be based upon temperature feedback from thermocouples within the test capsules. A secondary function of this system is to provide a carrier gas to transport gases emitted from experiments to a sample system. The sample system will be dependent upon experimenters needs.

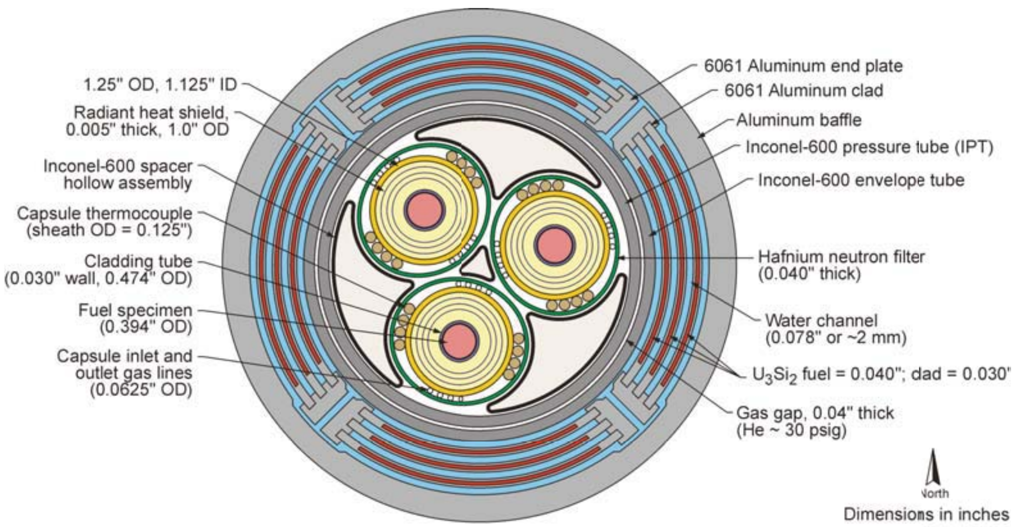


Figure 3. Axial cross section of the GTL conceptual design.

### 3.2. Thermal-hydraulic Analyses

Thermal hydraulic analysis was performed using RELAP5 to determine the steady-state operating temperatures for the GTL modified conceptual design. Figure 3 illustrates the configuration analyzed here. Each of the experiment locations is enclosed within a 1.25-inch OD tube. The test train configuration consists of three experiment tubes, each surrounded by an elliptical hafnium neutron filter. For analysis purposes, the filter shape is assumed to be circular. Two filter designs were analyzed – RC5 and RC5a. The configuration analyzed in case RC5a is identical to RC5 except that for case RC5a the neutron filters are clad with Inconel 600. Incorporation of the Inconel 600 cladding is proposed to prevent hydrogen embrittlement of the hafnium material at temperatures above 300 ºC (572 ºF), should that prove necessary. In both cases, each of the three neutron filters is 1 mm (0.040

in) thick. In case RC5a, the filters consist of a hafnium thickness of 0.75 mm (0.030 in) and a clad thickness of 0.125 mm (0.005 in) on each side. In case RC5, each of the three neutron filters is 1-mm (0.040-in) thick hafnium.

The annular region between the experiment tube and the neutron filter is cooled by flowing helium gas. Helium gas also flows in the region outside of the neutron filters and inside of the pressure tube. Helium is supplied to the test train at an upstream pressure of 2.086 MPa (302 psia) and 325 K (125 F) with an assumed pressure loss of 345 kPa (50 psid). The hollow spacer assemblies serve to reduce the flow area available for the helium coolant, thereby increasing its velocity and decreasing the required volume of helium to pump across the test loop. There are three spacers located between the experiment tubes and a fourth spacer at the center of the test loop. The spacers are constructed of Inconel 600 with a wall thickness of 0.5 mm (0.020 in) and are filled with stagnant helium gas.

The entire test train is enclosed within a structural mid-section, consisting of a pressure tube and an envelope tube, which are concentrically arranged and separated by a 1-mm (0.040-in) helium gap for leak detection monitoring. Outside of the envelope tube are three concentric rings of $U_3Si_2$ booster fuel clad with Al-6061. To be consistent with the ATR Safety Analysis, a 38.1 μm (0.0015-in) aluminum oxyhydroxide (boehmite) layer with a thermal conductivity of 2.25 W/m·K is assumed to exist on the surface of the fuel cladding. In reality, the surface layer will be only about 2 μm thick, so these calculations are very conservative for fuel core temperatures. All three fuel plates are 2.54 mm (0.100 in) thick with 1-mm (0.040 in) thick fuel meat. The entire arrangement of the test train and booster fuel assembly (BFA) is enclosed within a flux trap baffle made from Al-6061. The booster fuel is cooled with ATR primary coolant. The analysis assumes a pressure drop across the booster fuel of 497 kPa (72 psid), which is consistent with ATR 2 primary coolant pump operation. The booster fuel coolant flow rate is ~38 L/s (600 gpm).

Table 3 summarizes the maximum predicted temperature in each component. The maximum temperature of the neutron filter occurs at the inner diameter of the filter ring. The hottest temperature in the structural mid-section occurs at the outer diameter of the pressure tube. The maximum temperature of the booster fuel occurs at the centerline of the inner plate, as expected

**Table 3.** Predicted maximum steady-state heat structure temperatures for 150 kW experiment heat load.

| Heat Structure Component | Case RC5 | Case RC5a |
|---|---|---|
| Experiment Tube Surface | 554 K (538 ºF) | 551 K (532 ºF) |
| Filler Block | 417 K (291 ºF) | 414 K (286 ºF) |
| Neutron Filter | 466 K (379 ºF) | 461 K (370 ºF) |
| Pressure Tube | 450 K (350 ºF) | 449 K (349 ºF) |
| Booster Fuel | 518 K (473 ºF) | 520 K (476 ºF) |
| Booster Fuel Cladding Surface | 423 K (302 ºF) | 424 K (304 ºF) |
| Baffle | 345K (161 ºF) | 345K (161 ºF) |

### 3.3. Booster Fuel Qualification

The booster fuel will need to be qualified for service in the ATR. Qualification testing is anticipated to include irradiation testing of a number of mini-plates at varying power levels to evaluate any tendencies to corrosion of the fuel plate cladding. Another irradiation test planned is that of a single fuel plate manufactured by the booster fuel vendor. That will be followed by testing of a full assembly of 4 booster fuel elements.

Testing will be done to evaluate the performance of the fuel, e.g. to assess the mechanisms and likelihood of fuel failure. Such an assessment needs to be done with the understanding that the current booster fuel design is a direct extension of the existing ATR driver fuel design, with a minimum number of differences. The booster fuel is made with silicide rather than aluminide fuel meat. Booster fuel elements subsume twice the arc of driver fuel: 90 versus 45 degrees. The minimum radius of curvature of the booster fuel is tighter than that of the driver fuel [5.41 cm versus 7.66 cm (2.131 versus 3.015 inches)]. Finally, the booster fuel plates are only a little thicker than the thickest driver fuel plates in total thickness [2.55 mm versus 2.5 mm (0.120 versus 0.100 inches)], with a thicker fuel meat [1.0 mm versus 0.5 mm (0.040 versus 0.020 inches)]. Testing of reduced size fuel mini-plate specimens will reveal many mechanical, chemical, and thermal effects if they are significant. Testing of the full-sized curved plate and of the complete booster fuel assemblies will demonstrate that the fuel will perform as intended.

## 4. FUTURE WORK

There are still many issues requiring testing and analysis. The detailed mechanical design must be developed and the interfaces between the GTL and existing ATR systems finalized. Testing and qualification of the booster fuel elements must be performed. The details of the ATR driver fuel and GTL booster fuel cycles must be computed, and safety analyses must be performed at critical stages during the cycle. Issues relating to fuel and experiment transport, waste stream generation and disposal, reactor safety, and GTL life cycle management must be fully analyzed. Design work is continuing on these and other aspects, with submission of the CD-1 (critical decision 1 – approval for preliminary design stage) package planned for late FY 2007.

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